# Fast X-ray and optical variability of the Black Hole Candidate XTE J1118+480

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**Black holes become visible when they accrete gas; a close stellar companion is a common source of the gas. The standard theory ('thin accretion disk') for this process does not explain some spectacular phenomena, such as their X-ray variability[1] and relativistic outflows[2], indicating some lack of understanding of the actual physical conditions. Simultaneous observations at multiple wavelengths can provide strong constraints on the physics. Here were report simultaneous high-time-resolution X-ray and optical observations of the transient XTE J1118+480, which show a strong but puzzling correlation between the emissions. The optical emission rises suddenly following an increase in the X-ray output, but with a dip 2-5 s in advance of the X-rays. This result is not easy to understand within the simplest model of the optical emission, where the light comes from reprocessed X-rays. It is probably more consistent with the earlier suggestion[3] that the optical light is cyclosynchrotron emission that originates in a region about 20,000 km from the black hole. We propose that the time dependence is evidence for a relatively slow ($< 0.1c$), magnetically controlled outflow.**

The X-ray transient XTE J1118+480 (=KV UMa) provided a unique opportunity for simultaneous X-ray and optical observations because of its long duration (from January till August 2000), its proximity, and the lack

of obscuration at its position above the galactic plane[4–6]. The the orbit of the companion shows[5] that the central object has a mass $> 6$ $M_\odot$. We have obtained a total of 2.5 hrs of simultaneous observations distributed over 4 consecutive nights (July 4 through 7, 2000). The X-rays were strongly variable, in a mode typical[7] for black hole candidates (BHC) in the low-hard state, like Cyg X-1. The amplitude of the optical variability was smaller, about 10% rms on time scales of minutes and shorter. Results of another simultaneous observation (with RXTE and HST) have been announced earlier[8].

Correlations between the two time series are hard to identify reliably in the time series themselves, but are quite unambiguous by cross-correlation of segments as short as 1 min (Figure 1). An optical response starts within about 30ms following the X-rays, with a maximum reached after about 0.5 sec. The rapid variability of the optical emission (figure 2) excludes intrinsic thermal emission from a cool accretion disk as the source of the (variable part of the) optical emission.

The shape of the cross correlation as shown by fig 1 is quite suggestive of a simple explanation in terms of reprocessing[9,10]: X-rays from the central regions near the hole illuminate the upper layers of the surrounding accretion disk, and by heating these cause optical/UV radiation. The optical response is then easily modeled with an accretion disk inclined out of plane of the sky. The rapid rise would be due to the relatively short light travel time delay of photons reprocessed on the earth-facing half of the disk, and the slower decay arising from the longer path followed by photons reprocessed on the far side. On quantitative inspection however, this interpretation can be ruled out. The main problem is that the X-ray light curve does not have enough variability on time scales of 10-500 ms. With the observed X-ray autocorrelation (fig 2) a time lag of order a few seconds can be produced, but not the observed steep rise in the first few 100 ms. This is also evident from the optical variability itself. If the optical variation were due to reprocessing of the X-rays, its autocorrelation should be wider than that of the X-rays. This is the opposite of what is observed (fig 2). Secondly, there is significant variability in the cross correlation (fig 1, bottom), on time scales as short as 3 minutes. This is hard to explain as a variation in the reprocessing properties of the disk, since at 0.2-2 lightsec from the center the intrinsic time scales of the disk are much longer than 3 minutes. Some variation can be due to changes in the X-ray autocorrelation function, but quantitatively this again has problem of the lack of sufficient variability of the X-rays on

short time scales. Third, in X-ray binaries where reprocessing is indicated by independent evidence (such as Bowen fluorescence[11]) the optical-to-X-ray flux ratio is only a few per cent. This is much less than observed in XTE J1118+480, which had an optical luminosity[12] around $10^{35}$ erg/s, some 50% of the X-ray luminosity. Though our observations address only the (small) variable part of the optical emission, the unusually large optical flux itself is not easily explained either as reprocessed X-rays or as thermal emission from a cool disk.

A curious feature of the cross-correlation is the dip at 2–5s before zero lag (fig 3). The optical emission appears to decrease before the onset of an X-ray increase. This has been seen before in the BHC GX 339-4 (the only other source for which simultaneous X-optical observations at millisecond time resolution has been reported[13]). This feature poses a challenge for any model of the optical emission. Variations in the optical emission preceding the X-rays suggest a source of variation further out in the disk where (some of the) optical light may be produced, for example by a change in the mass flow rate. However, the optical signal would then require a *decreasing* mass flux preceding an X-ray increase. Cooling of the X-ray emitting region by inverse Compton scattering on optical/UV photons[3] would cause anticorrelated X-ray and optical variation, but any time delay would be much less than seconds.

Significant variability in the optical takes place on time scales as short as 100ms (see fig 1,2), hence the size of the optical emission region is not larger than a light travel distance of $3\,10^9$ cm. The observed optical brightness $\nu F_\nu = 1.5\,10^{-10}$ erg cm$^{-2}$s$^{-1}$ then yields a minimum brightness temperature of $2\,10^6$K for the inferred distance of the source (1.8 kpc). The radiation mechanism that most plausibly produces such brightness is cyclosynchrotron emission (CS) in a strong magnetic field[3]. To explain the (variable) delay of the optical emission, we interpret the emission region as the photosphere (surface of optical depth unity) in a magnetically dominated outflow from the central regions of the accretion. Modulations in the accretion rate onto the hole, evident in the X-ray light curve, are assumed to propagate into the outflow as modulations of the flow velocity and mass flux. Steepened into shocks, these modulations produce the observed radiation, as in the standard internal shock model of jet emission[14,15]. The optical variability reflects the passage of these modulations through the photosphere, and the optical delay of $\sim 0.5$s is identified with the travel time of the flow to the photosphere

from its origin near the hole. We find that this model is realistic only if the outflow has a rather low velocity, $v < 30000$ km/s. If the assumed velocity is too large, for example mildly relativistic, the photosphere is at such a distance (about $10^{10}$ cm) that the magnetic field of $\sim 10^6$G which is required to produce enough optical emission would be unrealistically high.

The outflow proposed here is not the same as that producing the observed radio emission, which is likely to originate from a less dense but faster flow, possibly a mildly relativistic jet[16,17]. Both kinds of outflow may be present at the same time, concentric to each other. The flow inferred here would then be the microquasar analog of, for example, the broad-line region outflows[18,19] of quasars, or the 'anomalous outflows'[20] of SS433. The CS outflow model is still tentative, however, since it does not naturally explain the prominent 'precognition dip' at negative lags.

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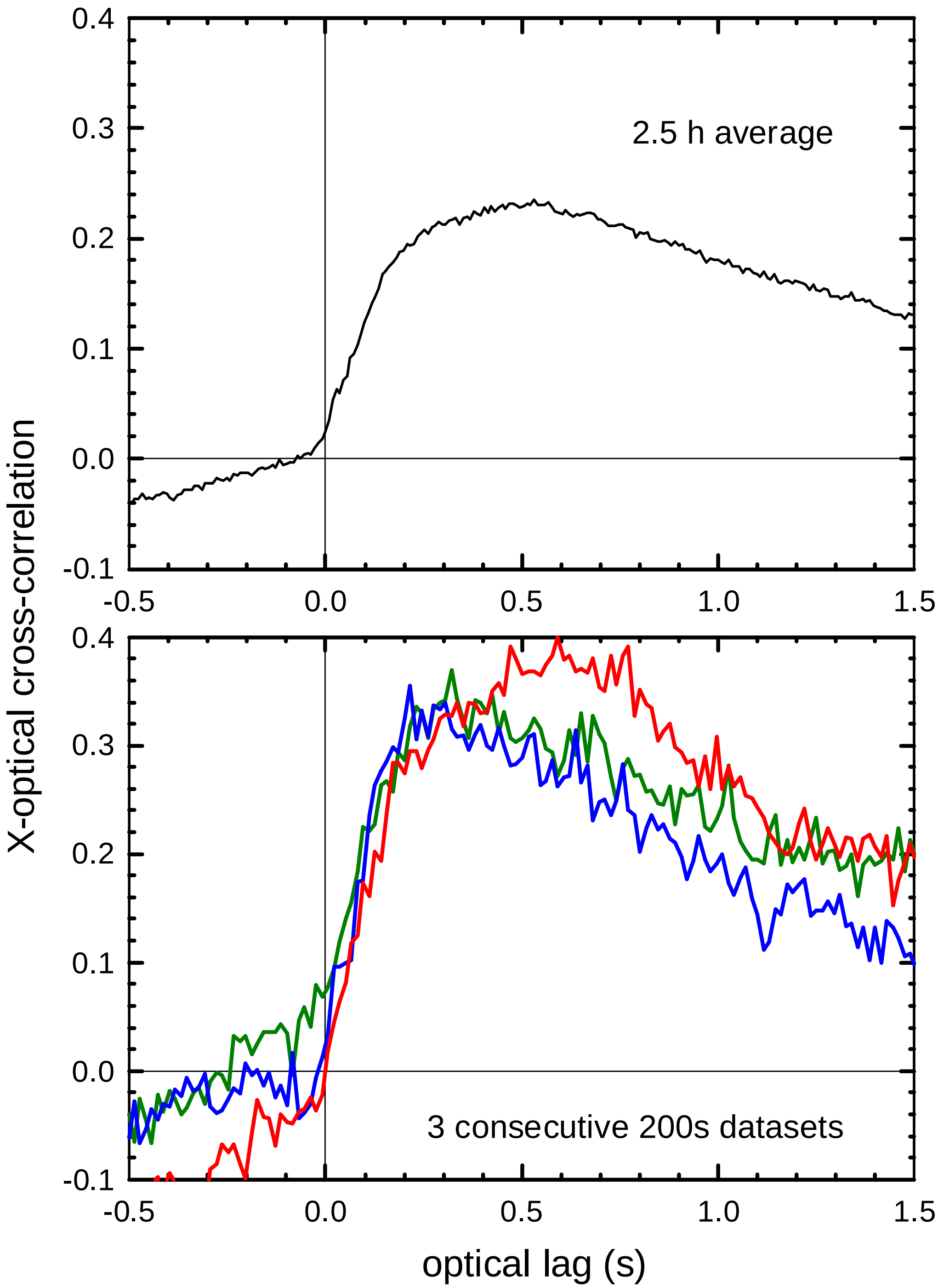
**Captions**

Fig. 1 Cross-correlation of the X-ray and optical time series of XTE J1118 +480, showing onset of an optical response within 30msec. Positive lag corresponds to delay of optical emission. Top: Average of all 2.5 hrs of data, bottom: a selection of 3 consecutive 200s segments of data, illustrating variability of the correlation. Piece-wise linear fits to 30s averages have been subtracted from both time series before correlating. The X-ray observations were made with the Rossi X-ray Timing Explorer[21], the optical observations with the OPTIMA photometer[22] attached to the 1.3m telescope at Mt Skinakas, Crete[23]. The photometer consists of a cluster of fiber-coupled avalanche photo diodes sensitive from 450 to 950 nm at a mean efficiency of 50%. Individual photon arrival times are recorded at 2 $\mu$s absolute accuracy using a GPS-based clock. Like in other observations of this source[24], a weak quasiperiodic oscillation of 0.08–0.1 Hz was present in the X-rays.

Fig. 2 Autocorrelations of the X-ray and optical time series, showing that the optical variability is not due to reprocessing of the X-rays. Time scales less than 70 msec are present in both the X-ray and optical light curves, but the optical autocorrelation is significantly narrower than the X-ray autocorrelation. If $f_{\rm x}(t), f_{\rm o}(t)$ are the X-ray and optical light curves and $g(t)$ the optical response of the disk to an infinitesimally short spike of X-rays, then $f_{\rm o} = f_{\rm x} * g$, where a $*$ denotes convolution. The X-ray/optical cross correlation is then $C_{\rm xo} = f_{\rm x} * f_{\rm o} = A_{\rm x} * g$ and $A_{\rm o} = A_{\rm x} * g * g$, where $A_{\rm x,o} = f_{\rm x,o} * f_{\rm x,o}$ are the X-ray and optical autocorrelation functions. In a reprocessing model, the optical autocorrelation must therefore be broader than $A_{\rm x}$.

Fig. 3 Correlation on time scales up to 30s, showing the enigmatic 'precognition dip' at negative lags of 2–5s. In the available models for the radiation from black hole candidates the optical light is produced either simultaneously with the X-rays, or later, by reprocessing of X-rays. Such models do not explain how the optical emission can 'know something' about X-ray emission that comes later.



X-optical cross-correlation
2.5 h average
3 consecutive 200s datasets
optical lag (s)
0.4
0.3
0.2
0.1
0.0
-0.1
-0.5
0.0
0.5
1.0
1.5




Figure 1:

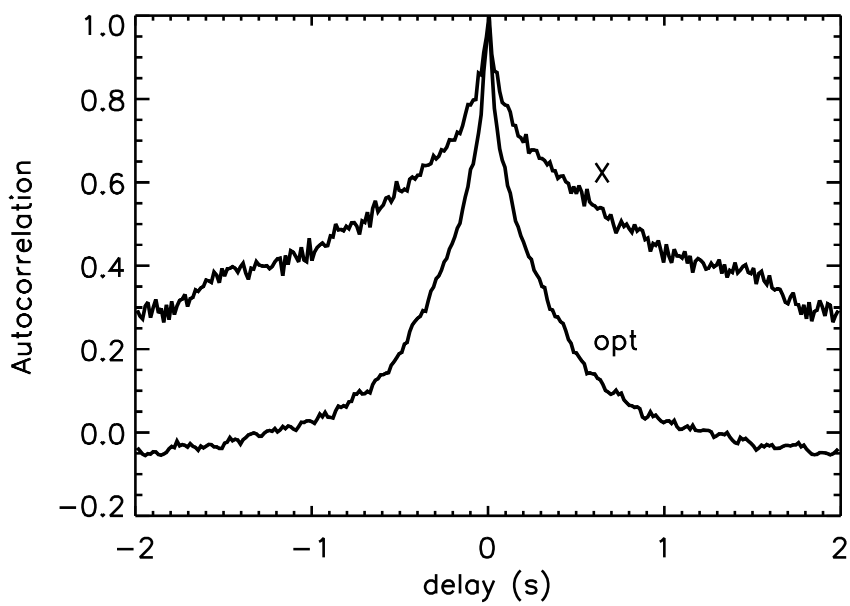



Figure 2:

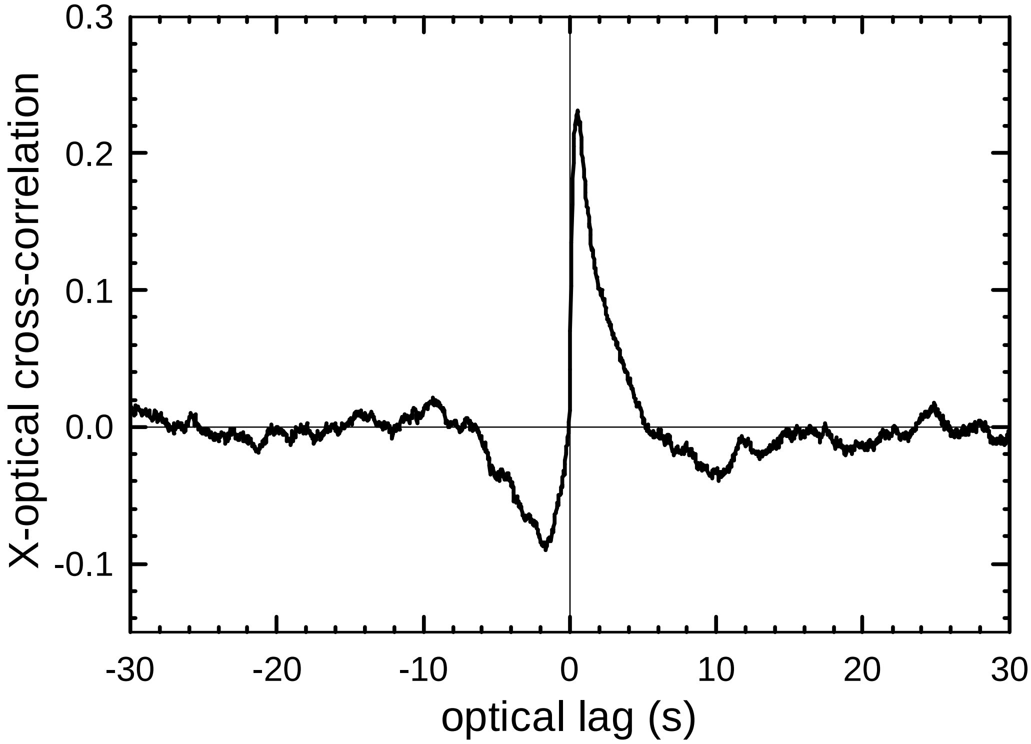

X-optical cross-correlation
0.3
0.2
0.1
0.0
-0.1
-30
-20
-10
0
10
20
30
optical lag (s)

Figure 3: